

Four Quark Interpretation of $Y(4260)$

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(Dated: February 2, 2008)

We propose that the $Y(4260)$ particle recently announced by BaBar is the first orbital excitation of a diquark-antidiquark state $([cs][\bar{c}\bar{s}])$. Using parameters recently determined to describe the $X(3872)$ and $X(3940)$ we show that the Y mass is compatible with the orbital excitation picture. A crucial prediction is that $Y(4260)$ should decay predominantly in $D_s\bar{D}_s$. The $Y(4260)$ should also be seen in B non-leptonic decays in association with one kaon. We consider the full nonet of related four-quark states and their predicted properties. Finally, we comment on a possible narrow resonance in the same channel.

ROMA1-1408/2005, FNT/T-2005/07, BA-TH/516/05

PACS numbers: 12.39.-x, 12.38.-t

In a series of exciting experiments, BELLE and BaBar have discovered several states that, although decaying in charmonium plus pions, do not seem to fit the $c\bar{c}$ picture, in particular the $X(3872)$ and $X(3940)$ states.

In a recent paper [1] we have pointed out that the properties of the new states can be well explained if they are S-wave diquark-antidiquark bound states with the composition $(q = u, d): [(cq)(\bar{c}\bar{q})]_{S\text{-wave}}$. An alternative scenario is the molecular picture where the $X(3872)$ would be a $D^0 D^{*0}$ bound state. A crucial difference between the two alternatives is that colored objects in a rising confining potential, such as diquarks, should exhibit a series of orbital angular momentum excitations. This is clearly at variance with the molecular picture. Colorless objects bound by a short range potential should have a very limited spectrum, possibly restricted to S-wave states only.

In this note we would like to propose that the first orbital excitation of a diquark-antidiquark state may have indeed been found in the state $Y(4260)$ recently announced by the BaBar collaboration [2]. We discuss the properties of the new state in this framework and spell out a few distinctive predictions. The most revealing among them is that the dominant decay mode of $Y(4260)$ should be in $D_s\bar{D}_s$ pairs. We shall also briefly discuss other states implied by the scheme and their properties. We comment on the possibility of an additional narrow state.

The $Y(4260)$ is observed by BaBar in e^+e^- annihilation, in association with an Initial-State-Radiation pho-

ton, which implies $J^{PC} = 1^{--}$. The particle has a width of about 90 MeV and it is seen to decay in $J/\psi \pi^+\pi^-$. The $\pi^+\pi^-$ mass distribution peaks around 1 GeV, consistently with a decay into $J/\psi f_0(980)$. BaBar reports the value [2]:

$$\Gamma(Y \rightarrow e^+e^-) \times Br(Y \rightarrow J/\psi \pi^+\pi^-) = 5.5 \pm 1.0^{+0.8}_{-0.7} \text{ eV} \quad (1)$$

The diquark-antidiquark assumption together with the negative parity call for at least one unit of orbital angular momentum. In addition, the decay into $f_0(980)$, which fits the $([sq][\bar{s}\bar{q}])_{S\text{-wave}}$ hypothesis [3], suggests a $[cs][\bar{c}\bar{s}]$ composition. All considered, we are led to the following assumption for the $Y(4260)$:

$$Y(4260) = ([cs]_{S=0}[\bar{c}\bar{s}]_{S=0})_{P\text{-wave}} \quad (2)$$

with both diquarks in a $\bar{\mathbf{3}}$ color state.

As discussed in [1] we expect diquarks involving charmed quarks to be bound also in states with non-vanishing spin (*bad diquarks* [4], with $S = 1$). Thus, several other states with $J^{PC} = 1^{--}$ are possible and one would expect the physical $Y(4260)$ to be a linear superposition of all such states. The state in (2) is supposedly the lowest lying among them and we restrict to it in this first analysis.

Following [1], a simple mass formula for the Y state can be given as follows:

$$M_Y = 2m_{[cq]} + 2(m_s - m_q) - 3\kappa_{cs} + B_c \left(\frac{L(L+1)}{2} \right). \quad (3)$$

$m_{[cq]}$ is the mass of the heavy-light diquark as computed in Ref. [1], i.e., $m_{[cq]} = 1933$ MeV, m_q and m_s are the constituent up and strange quark masses, respectively. A fit to the lowest lying meson and baryon masses, as reported in [1], gives $m_s - m_q = 185$ MeV. Spin-spin

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interactions are described by the Hamiltonian:

$$H_{\text{spin-spin}} = 2\kappa_{cs}(\vec{S}_c \cdot \vec{S}_s + \vec{S}_{\bar{c}} \cdot \vec{S}_{\bar{s}}) \quad (4)$$

and $-3\kappa_{cs}$ is its eigenvalue in the $S = 0$ state. The value of κ_{cs} is obtained from a fit to the charmed strange baryon spectrum and is reported in [1] as $(\kappa_{cs})_{\bar{3}} = 25$ MeV. In Eq. (3) we are neglecting spin-spin interactions between quarks and antiquarks (because of the angular momentum barrier which separates the diquark from the antidiquark) and the spin-orbit interaction (because of $S = 0$). In fact, the spin-orbit interaction can mix the good diquark, $S = 0$, with the bad diquark, $S = 1$, giving however only a second order correction to the mass that we provisionally neglect. These considerations lead to:

$$M_Y = 4160 + B_c \left(\frac{L(L+1)}{2} \right) \quad (5)$$

which leaves ~ 100 MeV for the orbital term, the only new ingredient with respect to Ref. [1]. We try different ways to estimate B_c from the corresponding terms in $q\bar{q}$ spectrum. We find somewhat different results, which gives an idea of the theoretical error involved.

We describe the masses of the $S = 1, L = 0, 1$ states $\rho(770), a_1(1230), a_2(1320)$ with the equation:

$$M(S = 1, L, J) = K + 2A_q \vec{S} \cdot \vec{L} + B_q \frac{L(L+1)}{2}. \quad (6)$$

One finds at once:

$$B_q = \frac{a_1 + a_2 - 2\rho}{2} = 0.495 \text{ GeV}. \quad (7)$$

For charm and beauty we take the difference between the lowest $S = 1, L = 0$ state and the center of $S = 1, L = 1$ mass spectrum and find:

$$B_{J/\psi} = 425 \text{ MeV}; \quad B_Y = 440 \text{ MeV}. \quad (8)$$

For the quantum rotator $B \propto (mR^2)^{-1}$, with R the radius of the bound state. Assuming the same radius and using $m_c = 1.3$ GeV and $m_{[cs]} = 2.1$ GeV as given above, we obtain from the light quark case:

$$B_c = \frac{m_q}{m_{[cs]}} \times 495 \simeq 120 \text{ MeV} \quad (9)$$

(scaling from charmonium we would get $B_c \simeq 260$ MeV).

An extreme alternative is to consider the diquark as a single constituent quark and scale the orbital terms as appropriate for Coulomb bound states. In this case, B scales like [5] $(R^2 M)^{-1}$ and $R = (\alpha_s M)^{-1}$ so that

$$B \propto \alpha_s^2 M. \quad (10)$$

This formula does not reproduce the values of $B_q, B_{J/\psi}, B_Y$ simultaneously. Using $\Lambda_{\text{QCD}} = 190$ MeV we find $B_{J/\psi} \simeq 340$ MeV, $B_Y \simeq 500$ MeV; for a slightly larger $\Lambda_{\text{QCD}} = 270$ MeV we find $B_{J/\psi} \simeq 135$ MeV,

$B_Y \simeq 170$ MeV. In correspondence $B_c \simeq 370$ MeV and 134 MeV respectively. The experimental Y mass clearly prefers a wider structure than charmonium but otherwise the orbital excitation picture is compatible within large theoretical errors:

$$M_Y^{\text{th.}} = 4330 \pm 70 \text{ MeV}. \quad (11)$$

Given the quantum numbers $J^{PC} = 1^{--}$, the state in Eq. (2) should decay strongly into a pair of mesons with open charm. The quark composition in (2) implies a definite preference for charm-strange states:

$$\Gamma_Y(D_s \bar{D}_s) \gg \Gamma_Y(D \bar{D}) \quad (12)$$

Dominant $D_s \bar{D}_s$ decay is quite a distinctive signature of the validity of the present model.

Quark diagrams corresponding to the $D_s \bar{D}_s$ and to the $J/\psi f_0(980)$ decays are reported in Fig. 1. Unlike the

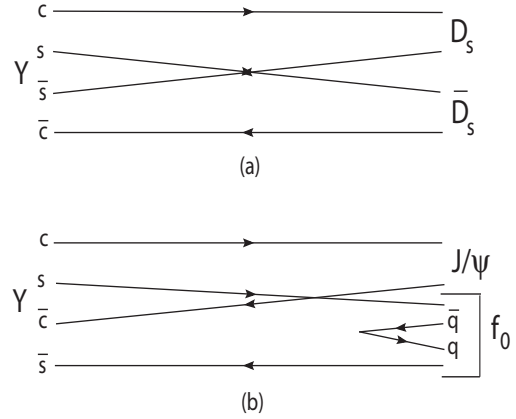


FIG. 1: (a) Quark diagram for the dominant decay channel to $D_s \bar{D}_s$ see Ref. [3]. (b) Decay amplitude for $Y \rightarrow J/\psi f_0(980)$ under the assumption that both Y and f_0 are four-quark states.

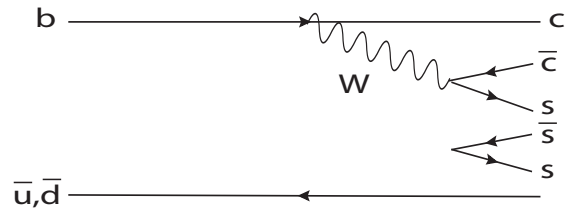


FIG. 2: Quark diagram for the weak decay of a $B^{-,0}$ meson into YK^- and YK_S . Kaons can be obtained in two independent way by combining the spectator antiquark with strange quark from the weak vertex or from the sea pair.

case of the $X(3872)$, the latter decay is not the dominant one. Assuming a partial width similar to the total

width of $X(3872)$, namely a few MeV's, one predicts a branching ratio for the $J/\psi f_0(980)$ channel in the order of $10^{-1} \div 10^{-2}$. The observation of BaBar, Eq. (1), therefore implies for the $Y(4260)$ a leptonic width of $50 \div 500$ eV, which is not unlikely for the one-photon production of such a complex state and consistent with the non-observation of this resonance in multihadron e^+e^- production around $E = 4$ GeV [6].

The $Y(4260)$ should be seen in B^- and B^0 weak non-leptonic decays, see the quark diagrams in Fig. 2, with:

$$\Gamma(B^0 \rightarrow YK_S) = \frac{1}{2}\Gamma(B^- \rightarrow YK^-). \quad (13)$$

Replacing the strange quark/antiquark with light quarks/antiquarks one obtains a full nonet of $J^{PC} = 1^{--}$ mesons. From the charm baryon spectrum one finds [1]: $(\kappa_{cs})_{\bar{\mathbf{3}}} \simeq (\kappa_{cq})_{\bar{\mathbf{3}}}$, so that the levels in the nonet are equispaced by $\simeq 185$ MeV (s=strangeness):

$$M_{Y(I=0,1;s=0)} = 3.91 \text{ GeV}; \quad M_{Y(I=1/2;s=\pm 1)} = 4.10 \text{ GeV}. \quad (14)$$

The neutral members of the non-strange complex should be seen in e^+e^- annihilation and in B non-leptonic decays (produced by diagrams like that in Fig. 2 with the $s\bar{s}$ pair replaced by $u\bar{u}$ or $d\bar{d}$). Dominant decay modes are in $D\bar{D}$. Similar to the $X(3872)$ case, a significant isospin breaking in the wave function of the non-strange

states can be expected. This should reflect in unequal branching ratios of each mass eigenstate in D^+D^- versus $D^0\bar{D}^0$. In the limiting case of pure $([cu][\bar{c}\bar{u}])_{\text{P-wave}}$ and $([cd][\bar{c}\bar{d}])_{\text{P-wave}}$ the first would decay in $D^0\bar{D}^0$ only and the second in D^+D^- . Decays into $J/\psi\pi^+\pi^-$ are expected to occur as well, with $\pi^+\pi^-$ peaking at the $\sigma(480)$ mass (restricted to the $I = 0$ state, if isospin would be conserved).

The BaBar data suggest, although inconclusively, that there may be a considerably more narrow satellite line at a mass $M \sim 4330$ MeV. We observe that this mass difference is of the order of the spin-spin interaction. Indeed, if one calls into play bad diquark states with $S = 1$ there are several additional 1^{--} states with the same quark composition, $(cs)(\bar{c}\bar{s})$. Among them, the state with both diquark and antidiquark spins in $S = 1$, combined to $S_{\text{tot}} = 2$. This state projects only on spin one $c\bar{s}$ and $s\bar{c}$ states. In the (not unrealistic) limit where the spin of the s quark is a good quantum number, such state could decay only into $D_s^*\bar{D}_s^*$ pairs, with substantial reduction of its decay width.

Acknowledgments. We wish to thank R. Faccini and A. Martin for useful information and interesting discussions. This work was partially supported by MIUR (Italian Minister of Instruction University and Research) and INFN (Italian National Institute for Nuclear Physics).

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